Comparison of IC and MEMS Packaging Reliability Approaches

Reza Ghaffarian, Ph.D.
Rajeshuni Ramesham, Ph.D.
Jet Propulsion Laboratory, California Institute of Technology
Reza.Ghaffarian@JPL.NASA.Gov, Tel:(818) 354-2059, Fax (818) 393-5245

ABSTRACT

During the last decade, research and development of microelectromechanical systems (MEMS) has shown a significant promise for a variety of commercial applications including automobile and medical purposes. For example, accelerometers are widely used for air bag in automobile and pressure sensors for various industrial applications. Some of the MEMS devices have potential to become the commercial-off-the-shelf (COTS) components. While high reliability/harsh environmental applications including aerospace require much more sophisticated technology development, they would achieve significant cost savings if they could utilize COTS components in their systems.

This paper reviews the current status of IC and MEMS packaging technology with emphasis on reliability, compares the norm for IC packaging reliability evaluation and identifies challenges for development of reliability methodologies for MEMS, and finally proposes the use of COTS MEMS in order to start generating statistically meaningful reliability data as a vehicle for future standardization of reliability test methodology for MEMS packaging.

INTRODUCTION

Packaging and testing of integrated circuit (IC) is well advanced because of the maturity of the IC industry, their wide applications, and availability of industrial infrastructure.[1,2] This is not true for MEMS with respect to packaging and testing. It is more difficult to adopt standardized MEMS device packaging for wide applications although MEMS use many similar technologies to IC packaging. Packaging of MEMS devices is more complex since in some cases it needs to provide protection from the environment while in some cases allowing access to the environment to measure or affect the desired physical or chemical parameters. The most of the silicon circuitry is sensitive to temperature, moisture, magnetic field, light, and electromagnetic interference. Microscopic mechanical moving parts of MEMS have also their unique issues. Therefore, testing MEMS packages using the same methodologies, as those for electronics packages with standard procedures might not always be possible especially when quality and reliability need to be assessed.

MEMS package reliability depends on package type, i.e. ceramic, plastic, or metal, and reliability of device. The MEMS device reliability depends on its materials and wafer level processes and sealing methods used for environmental protection. Package reliability issues are discussed in detail below. For completeness, some of the issues at the device level are also included.

IC PACKAGING TRENDS

SM electronic packages are mounted directly onto surface rather than inserting the leads into plated through-holes (PTHs). There are several surface mount package styles, both active and passive. Active devices are divided into those with terminations of leads on the periphery of the component, two or four sides, or those with terminations (either pads or solder bumps) over much of the bottom of the component. Peripheral array packages (PAP) such as quad flatpack (QFP) have less potential for significant size reduction with increased I/O (input/output) counts compared to area array packages (AAPs). The BGAs from the latter category are now the mainstay alternative to PAPs. For example, the CSP version of the two sided PAP is the lead-on-chip (LOC) package and the versions for AAPs are µBGA™, mini-BGA, and fine pitch BGA packages, generally with eutectic solder balls (see Figure 1).

Another level of miniaturization is accomplished by directly attaching the bare die to the PWB. The direct Flip Chip On Board (FCOB) is the ultimate miniaturization level achieving nearly 70% efficient use of the area of the die ratio to the PWB's footprint. In FCOB, solder bumps are permanently attached to the face of bare die, and the flip side is mounted on the PWB. In Chip-On-Board, with about 50% use of area efficiency, the pads of the wire bonded die are used for second level wire bonding onto the PWB.

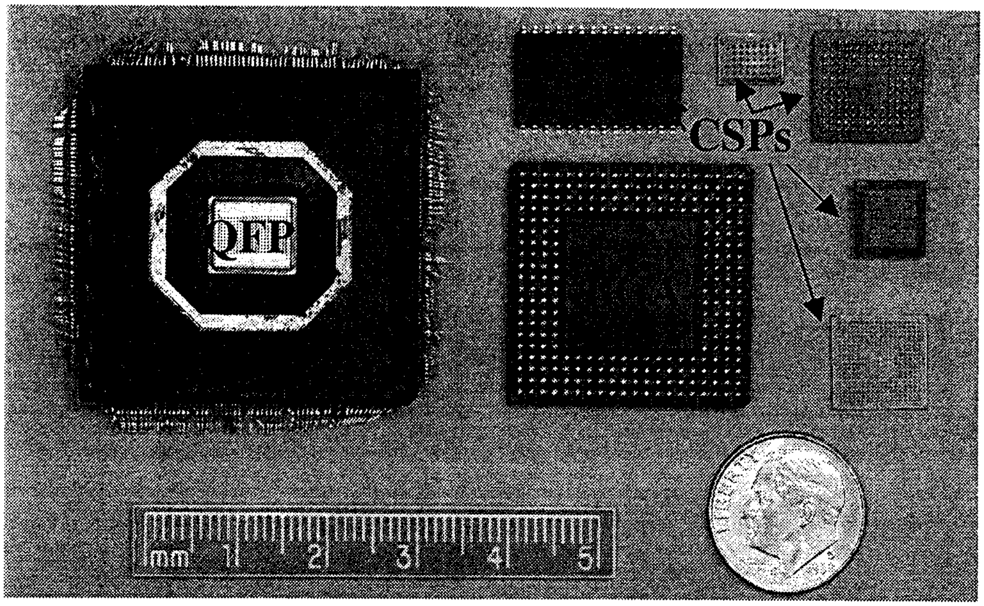

Figure 1 SM miniaturization from QFP to BGA and CSPs

Challenges on Reliability Characterization of Advanced IC Packages

Reliability, irrespective of its definition, is no longer an after-the-fact concept; rather, it must be an integral part of development and implementation. This is specifically true for microelectronics and MEMS with demands for miniaturization and system integration in a faster, better, and cheaper environment. Chip scale package, a near chip size package, is a good example which introduced into market and was rapidly adopted by industry for many applications including cell phones, camcorders, and telecommunications..

These new advanced IC packaging have their own unique form factor not seen in conventional surface mount technology and many of them may not be able to meet the traditional reliability test requirements. For examples, in additional to thermal cycling commonly used for assembly reliability, new specific tests such as bend and drop tests are being adopted to meet consumer portable device requirements. Adoption of such tests is further motivated by several factors including the following:

- Reduction in life expectancy for consumer electronics
- Rapid changes in electronic technology

For surface mount, solder has both electrical and mechanical functions and has been the weakest link in assembly reliability. This means that damage to solder could readily affect the functional integrity of the microelectronics system. Therefore, understanding the reasons for failure of defects that cause changes either in mechanical or electrical system characteristics is critical. The most common damages to solder joints are those induced by thermal cycling. Creep and stress relaxation are main causes of cycling damage. Creep for materials generally occurs at temperatures above half of the absolute melting temperature ($T/T_m > 0.5$). This value is 0.65 at room temperature for eutectic solder (63Sn/37Pb).

Thermal damage to solder joints is most often caused by the followings:

- Global CTE (coefficient of thermal expansion) mismatch between the package and board induces stresses. The package and board can also have temperature gradients through the thickness and at surface areas
- Local CTE mismatch between solder attachment to the component and the PWB

Reducing the CTE mismatch of component and PWB reduces cycling damage. For leaded surface mount packages, the CTE mismatch on solder joint was relieved by compliant lead. Rigidity of ball grid array (BGA) balls was one of reliability concerns at the start of their implementation. Experimental test results showed that BGA assembly failed either between ball and package or ball and PWB (solder joint)[1]. For grid CSPs, the interface between package and solder balls is also a potential failure site[2]. These failure mechanisms indicates that package/solder joint shear strength is also one of the key parameters that defines package susceptibility to both thermal and mechanical reliability.

Shear tests give an indication of deformation susceptibility and become especially critical for extreme mechanical conditions. Low values of shear force clearly indicated potential reliability concerns with CSPs. However, a few have been shown that CSPs survive the short duration shock and vibration conditions. Dynamic behavior is critical for applications of portable products where there is a potential of human mishandling such as accidental dropping.

For thermal cycling environments, several features of CSPs help its reliability. These include reduction in package size and therefore die size and package thickness. These will improve CSP reliability. For high reliability applications, especially packages with high I/Os, such improvements might not be sufficient, and other innovative technology development may be required in order to decrease the local and global CTE mismatch.

Innovative approaches had been developed aimed at absorbing CTE mismatch between the die and board within the package, or externally through strain absorbing mechanisms, therefore reducing stresses on the solder interconnects. These innovative approaches could introduce their own unique damage mechanisms since the weakest link now has been transferred from solder to other areas of the attachment system.

One innovative approach uses compliant tape automated bond (TAB) leads and elastomeric materials between die and substrate to reduce the package CTE mismatch. Since the TABs absorb the majority of stresses, this becomes the weakest link and a possible failure site. This approach has been widely shown to be effective for low I/O CSPs, but is yet to be proven for higher I/O CSPs. The other innovative approach which is called "Floating Pad Design" has potential for absorbing the global CTE mismatch and therefore, theoretically, handling a large I/O package. Test results by manufacturer are promising, but they are yet to be verified by others. It is not known if such solder ball floating would weaken the mechanical strength.

For innovative CSP design, failure at the board level could also be caused by solder joint or the internal package failure if design is not optimized. For example, package internal TAB lead failures at heels were reported for µBGA™ CSP— a fatigue failure shift from the solder joint to the internal package (see Figure 2). Significant reliability improvement was achieved when the TAB lead material, design, and lead forming were optimized.

This new type of failure is in contrast to the traditional theoretical wisdom where the solder joint failure is generally considered to be the weak link in solder joint assemblies. This and other failure mechanisms, which are being established for CSPs, must be understood by a modeler before he/she is to predict a meaningful reliability projection.

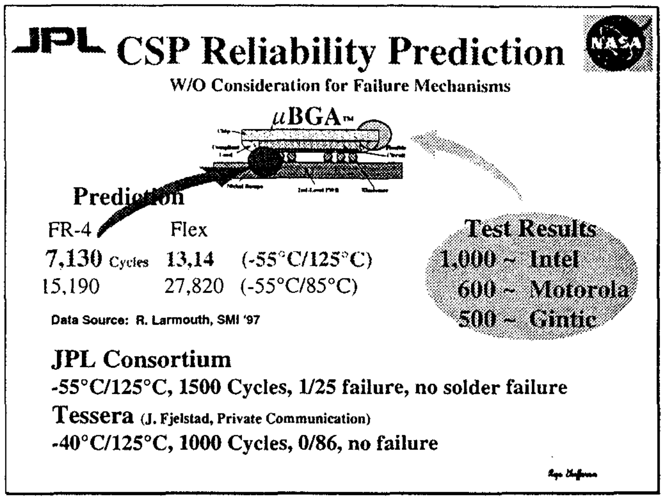

Figure 2 Fatigue failure projection based on the wrong failure mechanism assumption

MEMS PACKAGING CHALLENGES

Packaging of MEMS similar to IC technologies need environmental protection, electrical signal conduit, mechanical support, and thermal management paths. Packaging redistributes electrical signal paths from tight pad dimensions to over larger and more manageable interconnection leads. The mechanical support provides rigidity, stress release, and protection from the environment. Power distribution also needs to be taken into account for optimum packaging scheme. Thermal management is needed to support adequate thermal transport to sustain operation for the product lifetime.

Packaging of MEMS is considerably more complex as they serve to protect from the environment, while, somewhat in contradiction, enabling interaction with that environment in order to measure or affect the desired physical or chemical parameters. A package must also provide communication links through optimum interconnect scheme, remove heat through suitable selection of heat sinks, and provide robustness in handling and testing. The materials used for package should be selected to withstand not only handling during assembly and testing, but also throughout the operational environment of the product. Its robustness must be proven in terms of mechanical and thermal shocks, vibration, and resistance to chemical and other conventional life cycling tests especially needed for space applications.

The package must also be capable of providing an interior environment compatible with any particular constraints that may affect device performance and reliability. For example, a resonator might need a good vacuum for its operation and packaging scheme need to provide such requirement. MEMS can be integrated with associated electronics on the same chip to produce better electrical output. Integration can be done in the same wafer level or through wafer bonding or utilizing multi-chip module carriers.

Numerous papers published in literature regarding MEMS packaging issues. For example, Frank et al,[3] has provided detailed overview of the packaging tools that are required for sensors. Senturia and Smith[4] have highlighted the importance of system partitioning, package design and process optimization when building the electronic components and sensor structures as part of the single device. Reichl[5] have described the requirements for packaging technologies, bonding techniques, chip-substrate interconnection techniques, and alternative chip integration techniques to deliver reliable, economical, and application specific solutions by choosing optimized technologies and appropriate materials combinations.

Kim[6] has described packaging scheme of pressure sensor arrays utilizing multi-chip modules and tape automated bonding (TAB) carrier. This one was developed specially for aerospace and aircraft applications thus requiring thin profile packaging with high accuracy.

MEMS Reliability

Reliability requirements for various MEMS will be significantly different from one application to another especially where the systems incorporating MEMS components are unique. Standardized reliability testing is not possible until common set of reliability requirements is developed. Literature survey on MEMS reliability issues produced limited information but valuable results.

Romig et al,[7] identified a list of packaging reliability concerns for microsystems. Factors mentioned that affect the MEMS packaging included tribological behavior, contamination, cleaning stiction, and typical mechanical fatigue issue. Brown et al,[8] reported characterization of MEMS fatigue on polysilicon. Reliability assessment for media compatibility for a gas sensor produced coating requirements[9] while a need for new device passivation and alternative chip mounting techniques was identified by Dyrbye et al.[10]

Miller et al,[11] reported reliability testing of surface micromachined microengine whose analysis concluded the prevailing failure mode was the gear sticking to the substrate or to the hub and showed that significant portion of the microengine failure was infant mortality. In another paper, Tanner et al,[12] observed a large amounts of debris in the areas of microengine rubbing which led to the failure of drive gears. They have also presented qualitative and predictive model for actuator reliability. In their recent study, the effect of moisture content on failure by wear mechanism was determined. It was shown that as the humidity decreased the volume of debris generated increased. For the higher humidity levels, the formation of surface hydroxides considered to act as a lubricant resulting in lower amounts of wear debris. Patton et al,[13] also showed the effect of humidity on failure mechanism for MEMS electrostatic lateral output motor. Electrical performance degraded with increased humidity whereas mechanical seizure showed mixed results. At a very low and high humidity, failure occurred mechanically and electrically, respectively, whereas improvement observed below and above 40% RH. Kelly et al,[14] have described the issues how packaging influence the reliability and performance characteristics of MEMS.

JPL has been very active in MEMS characterization and their implementation for aerospace applications. For example, an extensive reliability testing of MEMS devices especially for space applications was done by Muller et al,[15] who provided a comparison for testing environments for space applications with automotive environment. Tang et al,[16] have described extensively on design, fabrication, and packaging of a silicon MEMS vibratory gyroscope for microspacecraft applications. Miller et al,[17] have described an overview of MEMS development for micro- and nano-spacecraft application and emphasized the reliability, packaging, and flight qualification methodologies that need to be developed for MEMS to produce robust MEMS for space applications. Hartley[18] discussed the requirements of a nano-g accelerometer developed by NASA in collaboration with Northeastern University for the tri-axial measurement of orbital drag on the Shuttle and Space Station. It required an acceleration range of 10^{-2} to 10^{-8} g over a frequency range of 0.001-25 Hz.

High Volume MEMS Applications

The most mature MEMS devices are pressure sensors and accelerometers. The manifold absolute pressure (MAP) sensor has been used in automobile industry since 1979.[19] Today, many automobiles have one of these sensors in their electronic engine control system. Pressure sensors also widely used for medical invasive blood pressure sensor applications. Accelerometer is being used for an airbag crash sensor in automobile since 1990. In addition to significant mass reduction, the integration of diagnostic characteristics into sensors, enable device internal failure detection.

Micromachined accelerometer includes mechanical flexure-supported masses and assembled sensors. The sensor is assembled via integration and then in a closed-rigid package. The sensor consists of a set of fixed beams and a moveable beam structure to sense relative movement. The beam to beam closeness could cause stiction. Hartzel et al,[20] developed a methodology for prediction of stiction-related field failures.

Spangler[21] presented development of IC package for micromachined accelerometer for automotive applications. In their recent developmental activities, the use of surface mountable package rather than single in line through package (SIP) was engineered. The surface mountable device (SMD) version gave more life to the existing die product and at the same time, that has met requirements for surface mount components.

MEMS Reliability and Key Failure Mechanisms

Almost all cited reliability-testing issues were summarized for a certain application and cannot usually be used for any other application to benchmark. Understanding of MEMS reliability and technology assurance issues are key to their wider acceptance towards high reliability applications as well as technology transfer their commercialization. MEMS reliability is one of the most difficult questions to answer since they are still in their infancy, developed for specific applications, and reliability requirements vary and finally, which frequently depend on the user requirements. In spite of differences, similar common methodologies could be developed for assessing qualification and reliability for those with similar failure mechanisms.

A critical part of understanding the reliability of any system comes from understanding the system failure behavior and their mechanisms. For IC package assembly, failure generally related to solder joint.[2] In MEMS, there are several failure mechanisms that have been found to be the primary sources. These include:

- **Failure by Stiction and Wear:** Contrary to solder joint failure for IC system failure, thermal cycling fatigue failure for MEMS are of less critical. Stiction and wear, however, are real concern and cause most failures for MEMS. MEMS failure may occur due to microscopic adhesion when two surfaces are come into contact which is called stiction. Microscopic separations generally induce particulate which when caught between micro parts will stop part movement. Wear due to corrosive environment is another aspect of such failure.
- **Environmentally induce failures**: Failure due to thermal cycling, vibration, shock, humidity, radiation effect, etc. are commonly observed for MEMS and IC packaging systems. MEMS devices because of having additional mechanical moving parts, are more susceptible to environmental failure than their IC packaging systems.
- **Cyclic mechanical fatigue:** This is critical for comb and membrane MEMS devices where materials are subjected to alternative loading. Even if the load is such that it is significantly below failure, the stress can cause degradation in materials properties. For example, changes in elastic properties affect resonant and damping characteristics of beam and therefore degrade MEMS sensor outputs.
- **Dampening Effect:** Dampening is not critical for IC packaging, but it is critical for MEMS devices, which operate with moving parts at their resonant frequency. Dampening can cause by many variables including presence of gas in atmosphere. Therefore, good sealing is essential for avoidance of such failure.
- **Delamination:** Delamination of thin film material bonded to another surface is a concern. Delamination can cause catastrophic failure or degrade device function due to alteration of materials characteristics.

DISCUSSION

Contrary to IC packaging, a single set of reliability testing requirements for a wide application may not be possible for evaluation of MEMS technology. However, finding a common denominator and standardized testing based on the MEMS key failure mechanisms are valuable to user community. The users can carry out then any additional reliability testing specifically needed for their applications thus minimizing the cost of new technology implementation.

In order to generate statistically meaningful data on quality and reliability and to understand key failure mechanisms, COTS MEMS with potential for high reliability applications are considered for evaluation. Similarly to IC packaging programs[1,2], JPL has initiated forming a consortium with industry participation with the objectives of understanding quality and reliability assurance associated with implementation of this technology and help to build needed infrastructure. Consortium will emphasize development of test methodologies for characterizing reliability of MEMS including pressure sensors and accelerometers.

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BIOGRAPHY

Dr. Reza Ghaffarian has 20 years of industrial and academic experience in mechanical, materials, and manufacturing process engineering. At JPL, Quality Assurance Section, he supports research and development activities in SMT, BGA, CSP, and MEMS technologies for infusion into NASA's missions. He has authored nearly 100 technical papers and numerous patentable innovations. He is a frequent speaker and chaired technical conferences including SMTA International, IMAPS, ASME, SAMPE, NEPCON, SEMI, IEEE CPMT, and IPC. He received his M.S. in 1979, Engineering Degree in 1980, and Ph.D. in 1982 in engineering from University of California at Los Angeles (UCLA).